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THE BLIND RIVER URANIUM DEPOSITS: THE ORES AND THEIR SETTING[1]

by

James A. Robertson

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ABSTRACT

In the Blind River area, Proterozoic clastic sedimentary and minor volcanic rocks of the Huronian Supergroup unconformably overlie and transgress northward over dominantly granitic Early Precambrian (Archean) terrain (2,500 million years) and are intruded by Nipissing Diabase (2,150 million years). Deformations and metamorphic events later than these have been recognized.

The Matinenda Formation (basal Huronian) comprises northward-derived arkose, quartzite, and pyritic, uraniferous oligomictic conglomerate that contain 75 percent of Canada's uranium reserves. Historic grades approximate 2 lbs. U_3O_8/ton, but lower grade material can be mined as the price of uranium increases. Some thorium and rare earths have been marketed. The general absence of gold reflects a lack of this metal in the source area.

The conglomerate beds occur in southeasterly striking zones controlled by basement topography down-sedimentation from radioactive Archean granite. The distribution of monazite relative to that of uraninite and "brannerite" and the presence of uranium values in overlying polymictic conglomerates which truncate the ore-beds, indicate that the mineralization is syngenetic, probably placer. The role of penecontemporaneous mafic volcanic rocks is problematical, but these could have been a source for sulphur in the pyrite.

Drab-coloured rocks, uranium and sulphide mineralization, and a post-Archean regolith formed under reducing conditions, suggest a reducing environment. Sedimentary features indicate deposition in fast-flowing shallow water, and possibly a cold climate. In the upper Huronian (Lorrain Formation), a monazite-iron oxide assemblage associated with red beds suggests a change to oxidizing conditions.

Similar deposits occur at Agnew Lake, and polymictic conglomerate and siltstone found north of Sudbury carry minor uranium, and locally gold values. Provenance, lack of oxygen, transportation and depositional processes, and no major modification by later events are the dominant factors in the formation and preservation of the ore bodies.

Research is needed on: mineralogical relationships; detailed sedimentology of the conglomerates; and, on the volcanic rocks, their nature and role, if any, in the formation of the uranium deposits.

Figure 1 — Location of Blind River-Elliot Lake area.

THE BLIND RIVER URANIUM DEPOSITS:

THE ORES AND THEIR SETTING

by

James A. Robertson[1]

INTRODUCTION

The Blind River uraniferous pyritic oligomictic conglomerates were found in 1953 since which date the activities of mining companies, the universities, and of both Canadian and Ontario Government geologists have given rise to a large body of literature and other data. This paper is an attempt to summarise the present state of knowledge, to provide guidelines for the exploration geologist, or to the geologist in the field who could be in favourable terrain. The paper is in three sections; first, a description of the regional geology; second, a description of the ore-bearing conglomerates; and third, a discussion of those factors that are of genetic significance.

REGIONAL GEOLOGY

Blind River (Figure 1) lies on the North Shore of Lake Huron, halfway between Sudbury and Sault Ste. Marie. The town of Elliot Lake built to service the uranium mines lies 32 km (20 miles) northeast of Blind River.

The region lies on the boundary between the Southern and Superior Provinces of the Canadian Shield. The Superior Province (Goodwin *et al.* 1972) comprises Archean rocks which were affected by the Kenoran Orogeny (2,500 million years) and the Southern Province (Card *et al.* 1972) includes Proterozoic rocks affected by the Penokean Orogeny (1,750 million years). The Blind River-Elliot Lake area lies at the margin of early Proterozoic sedimentation and of the mid-Proterozoic metamorphism.

Table 1 is a Table of Formations using the nomenclature recommended by the Federal-Provincial Committee on Huronian Stratigraphy (J.A. Robertson *et al.* 1969) and Table 2 permits comparison with schemes used in publications before 1969. Table 3 provides a synopsis of the stratigraphy and the relationship to mineralization (see section on "Summary").

The bedrock of the area falls into three broad units, the distribution of which is shown on Figure 2a. These are: (1) the Archean basement, consisting of Keewatin-type "greenstone", Algoma granite and minor mafic intrusive rocks; (2) the Huronian sedimentary rocks and metasediments with local minor mafic volcanic rocks and (3) the post-Huronian intrusive

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TABLE 1 | TABLE OF FORMATIONS FOR THE BLIND RIVER-ELLIOT LAKE AREA.

UNIT	CODE	DOMINANT LITHOLOGY	AGE (Million Years)
PHANEROZOIC			
CENOZOIC			
PLEISTOCENE AND RECENT		Sand, gravel, till	
UNCONFORMITY			
PALEOZOIC			
ORDOVICIAN	(20)	Limestone	
PRECAMBRIAN			
PROTEROZOIC (LATE AND MIDDLE PRECAMBRIAN)			
KEWEENAWAN SUPERGROUP			
Sudbury Dikes	(19)	Olivine diabase	1,225
INTRUSIVE CONTACT			
Mount Lake Dike		Quartz diabase	
INTRUSIVE CONTACT WITH NIPISSING DIABASE			*
HUDSONIAN			
Croker Island Complex	(18)	Gabbro, granite	1,445
Cutler Batholith	(18)	Granite	1,750
INTRUSIVE CONTACT			
PENOKEAN			
Nipissing	(17)	Quartz diabase, diorite	2,155
INTRUSIVE CONTACT			
HURONIAN SUPERGROUP			
Cobalt Group			
Bar River	(16)	Quartzite	
Gordon Lake	(15)	Siltstone, sandstone	
Lorrain	(14)	Quartzite, conglomerate, arkose	
Gowganda	(13)	Conglomerate, greywacke, quartzite	
UNCONFORMITY-DISCONFORMITY			
Quirke Lake Group			
Serpent	(12)	Quartzite	
Espanola	(11)	Limestone, siltstone	
Bruce	(11)	Conglomerate	
LOCAL DISCONFORMITY			
Hough Lake Group			
Mississagi	(10)	Quartzite	
Pecors	(9)	Argillite	
Ramsay Lake	(8)	Conglomerate	
LOCAL DISCONFORMITY			

UNIT	CODE	DOMINANT LITHOLOGY	AGE (Million Years)
Elliot Lake Group**			
McKim	(7)	Argillite	
Matinenda	(5)	Quartzite, ± U-conglomerate Conglomerate Arkose ± U-conglomerate regolith	
UNCONFORMITY			
ARCHEAN (EARLY PRECAMBRIAN)			
LATE ARCHEAN INTRUSIVES		Diabase	2,500
INTRUSIVE CONTACT			
KENORAN (ALGOMAN)	(3)	Granite	2,500+
INTRUSIVE CONTACT			
EARLY ARCHEAN INTRUSIVES		Gabbro	
INTRUSIVE CONTACT			
KEEWATIN	(1)	Volcanic and sedimentary rocks	c 2,400

* Mount Lake Dike may be 1,795 m.y.

** Volcanic rocks are found locally in the Elliot Lake Group (6), each occurrence has been given its own name.

Note: Geological ages given are from a variety of sources.

TABLE 2 SYSTEMS OF HURONIAN STRATIGRAPHIC NOMENCLATURE

COLLINS, 1925		ROBERTSON, 1967		ROSCOE, 1960		ROBERTSON *et al.* 1969	
Cobalt Series	Upper White Q.[1]	Cobalt Group	Bar River	Cobalt Group	Upper White Q.[1]	Cobalt Group	Bar River
	Banded Cherty		Gordon Lake		Banded Cherty		Gordon Lake
	Lorrain		Lorrain		Lorrain		Lorrain
	Gowganda		Gowganda		Gowganda		Gowganda
Bruce Series	Serpent	Bruce Group	Serpent	Quirke Lake Group	Serpent	Quirke Lake Group	Serpent
	Espanola		Espanola		Espanola		Espanola
	Bruce		Bruce		Bruce		Bruce
	Mississagi		Upper Mississagi	Hough Group	Mississagi	Hough Lake Group	Mississagi
			Middle Mississagi Argillite		Pecors		Pecors
	(Ramsay Lake)		Conglomerate		Whiskey		Ramsay Lake
	Granites		Lower Mississagi Argillite	Elliot Group	Nordic	Elliot Lake Group[2]	McKim
Archean Sudbury Series	McKim		Quartzite		Matinenda		Matinenda
		Archean	Algoman	Archean		Archean	
Archean	Schist Complex		Keewatin				

[1] Q = Quartzite
[2] Volcanic rocks are found locally in the Elliot Lake Group.

rocks, comprising the Nipissing Diabase sills, post-Nipissing Diabase dikes, the Cutler Granite, the Croker Island Complex and olivine diabase believed to be Keweenawan in age (only the Cutler Batholith and the Croker Island Complex are shown on Figure 2a). The structure is also illustrated in Figure 2b. In the north-central zone lies the Quirke Syncline; farther north is the Flack Lake Fault, with upper Huronian rocks exposed on the downthrow (north) side; and in the centre is the Chiblow Anticline, the south limb of which is repeated by a major east-striking fault called the Murray Fault. The axes of these folds strike slightly north of west and plunge gently west, giving the sedimentary units a reversed S-shaped outcrop. To the south of the Murray Fault, east of Algoma, the folding and metamorphism are more intense and complex. To the east of the Cutler Batholith, fold axes and other linear features generally plunge eastward, but to the west of the batholith the linear structures plunge westward. Only the most clearly defined folds are shown in Figure 2. The eastern end of the Cutler Batholith is controlled by the Spanish Anticline (J.A. Robertson 1966a, 1975a; Cannon 1967). The La Cloche Hills are defined by the Lorrain quartzite, which forms the limbs of the La Cloche Syncline. The Crocker Island Complex lies near the axis of the McGregor Bay Anticline. When traced eastwards, the La Cloche Syncline and the McGregor Bay Anticline are part of a series of folds trending easterly between Espanola and the Grenville Front (Card 1967a, b, c, and d; Young 1966; Young and Church 1966).

Bedding-plane slips, thrust faults and near-vertical faults, which strike either northwest or parallel to the axial planes of the folds, are common. The fault pattern, jointing pattern, slickensides on bedding planes, and drag-folds suggest that north-south compression formed the folds. Several periods of intensity of deformation and metamorphism can be demonstrated.

Archean (Early Precambrian)

Keewatin-Type Rocks

Keewatin-type rocks of Archean age are found locally in the area bordering the North Shore of Lake Huron, and underlie the Huronian rocks near Elliot Lake. The rock types found include massive and pillow lavas, pyroclastic rocks, and sedimentary rocks, including lean iron formation. The strike is northwest, and dips generally steep to the northeast. Metamorphism is of the chlorite grade rising to the amphibolite grade in hybrid zones close to contacts with the Algoman granite. The general lack of "greenstone" in the cratonic block north of the Huronian basement, and a low frequency of known gold occurrences in the area believed to be the source area, are mirrored in the lack of gold in the uraniferous conglomerates.

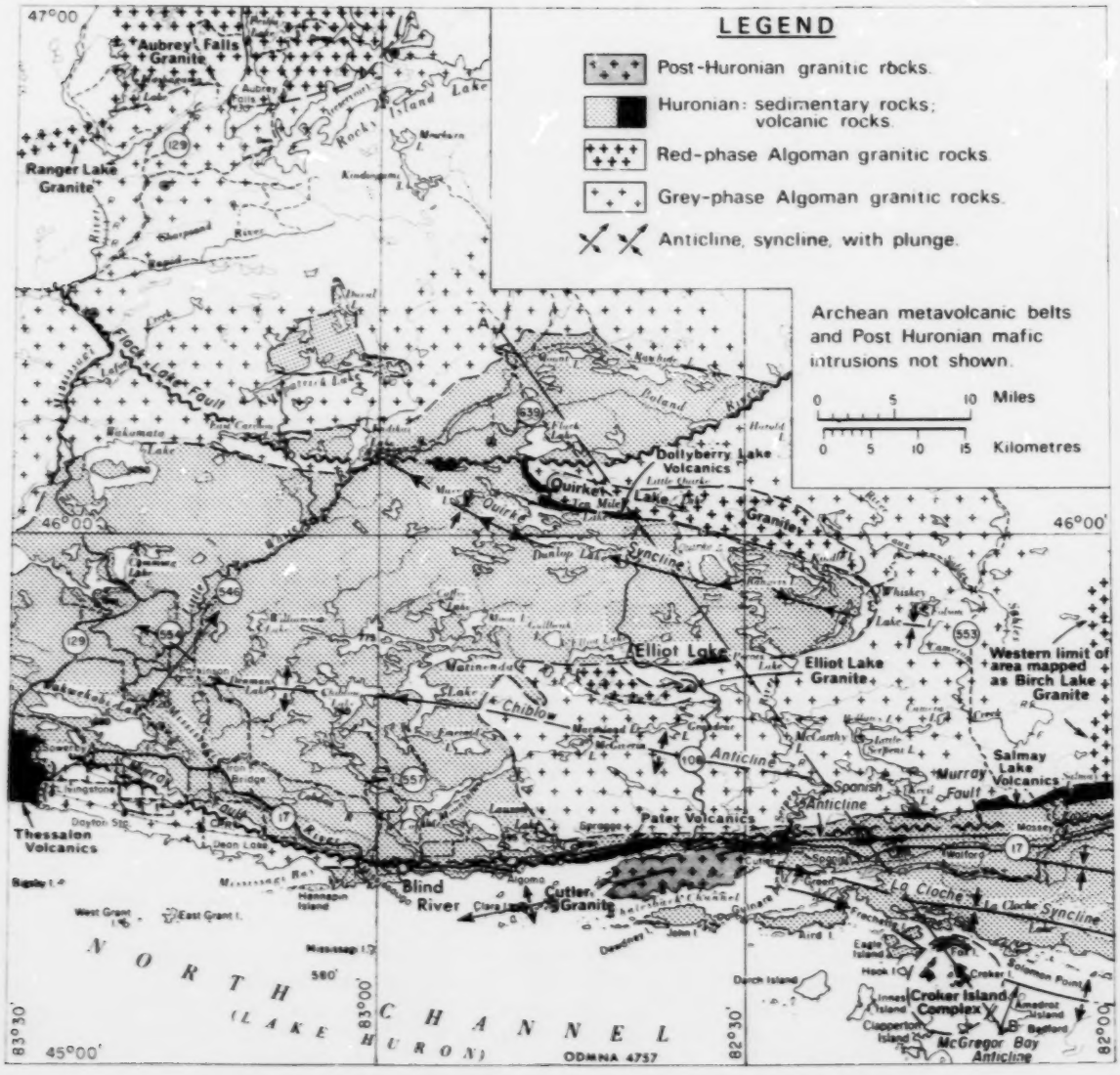

Figure 2a — Generalized geological map of Blind River-Elliot Lake area.

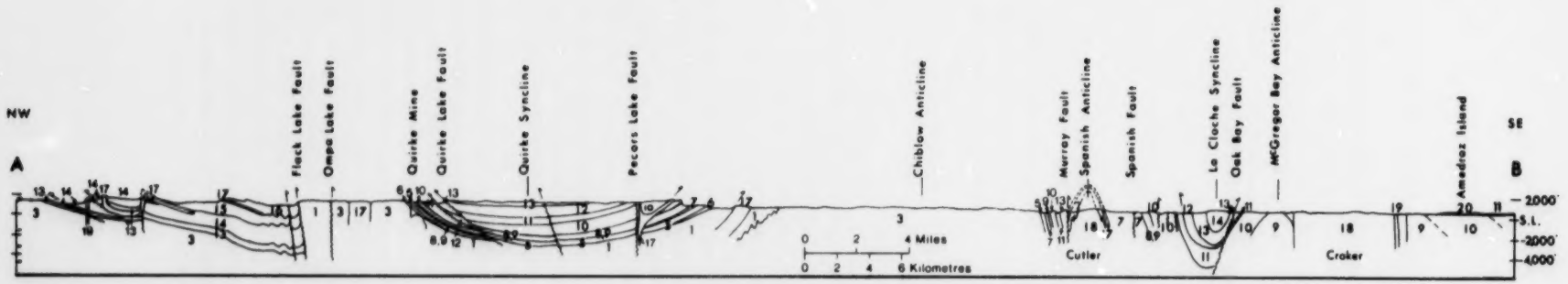

Figure 2b — Schematic cross-section Elliot Lake area, units keyed to Table of Formations; line of section shown on Figure 2a.

Algoman Granitic Rocks

Granitic rocks of Algoman age (2,500 million years: Lowdon 1960, 1961; Lowdon, Leech, Stockwell, and Wanless 1963; Lowdon, Stockwell, Tupper, and Wanless 1962; Van Schmus 1965; Wanless *et al.* 1965) underlie approximately half the area shown on Figure 2. These granitic rocks may be divided into two broad groups: (1) medium- to coarse-grained, gneissic to massive granodiorite, generally grey to pink in colour with abundant inclusions of Keewatin-type rocks, and (2) massive red quartz monzonite, generally without inclusions and slightly radioactive. Bodies of the second type are found in the Quirke Lake, Aubrey Falls-Ranger Lake and Elliot Lake areas (Figure 2), (J.A. Robertson 1960, 1961, 1968a; J.A. Robertson and McCrindle 1967).

It is of interest that in the Montreal River Area north of Sault Ste. Marie, and eastwards as far as Aubrey Falls, there are occurrences of pitchblende coating joints in the granitic rock, and pitchblende associated with the contact of Late Proterozoic (Late Precambrian) diabase and Archean (Early Precambrian) granite. In the same area uraninite occurs in Archean pegmatite (Nuffield 1955; J.A. Robertson 1968b, 1975a). From a statistical analysis of crossbedding and size distribution of chert pebbles in the Mississagi Formation McDowell (1957) indicated that the source area for the Lower Huronian lay 210 to 400 km (130 to 250 miles) west-northwest of Thessalon.

More recently an airborne gamma-spectrometer survey has confirmed that much of the granitic terrain north and northwest of the Elliot Lake area contains anomalous amounts of uranium (Darnley and Grasty 1971; Richardson *et al.* 1975). In general those areas containing the massive red quartz monzonite exhibit anomalous uranium content.

The massive red granitic rocks of the Archean basement are thought to be the source of the uranium found in the Huronian conglomerate.

After the peak of the Kenoran Orogeny the area was fractured and numerous diabase dikes were intruded. The region was then subjected to a prolonged period of weathering and peneplanation. During this period hollows or valleys developed over the more easily eroded rocks, such as those comprising the greenstone belts. Throughout the Blind River Area, partially weathered zones have been preserved under the Huronian-Archean unconformity, and particularly over the granitic rocks.

At distances greater than 90 m (100 yards) from the contact with the overlying Huronian, the granitic rocks exposed at the surface are of the normal type. However, as the actual contact is approached, the plagioclase feldspar grains become yellow, owing to the development of sericite, and the ferromagnesian minerals are no longer present. The granitic texture is preserved by the quartz and microcline crystals. The above material passes into an unsorted aggregate of partly corroded quartz and microcline grains in a yellow-green matrix of sericite. Rarely, angular fragments of vein quartz and patches of less-altered granite may be present. This material is overlain by sorted sericitic arkose, in which bedding and crossbedding are generally visible. In some outcrops the actual contact may be marked by a band of angular to subangular quartz fragments up to an inch across.

This transition zone is generally interpreted (J.A. Robertson 1960 *et seq.*; Roscoe 1957 *et seq.*) as a regolith or fossil weathered zone developed during the Archean-Proterozoic Interval. Such weathered zones have been observed over both red-and grey-phase Algoman granites. Sections of diamond-drill core also show the development of crumbly chloritic material between the "greenstone" and the overlying sedimentary rocks (Rice 1959). This has also been regarded as regolith. Both Pienaar (1963) and J.A. Robertson (1960 *et seq.*) have analysed samples of regolith. Figure 3, derived from their analyses, is a straight line diagram illustrating the development of the regolith. The following features are apparent:

a) Silica is constant and there is a slight gain in alumina.
b) Zirconia is constant, reflecting stability of zircon.
c) Total iron, and both ferrous and ferric iron show marked loss, ferric iron is lost more completely than ferrous iron.
d) Magnesia and manganese have been partially lost.
e) Lime, strontia, and soda have been markedly reduced.
f) Potassium, rubidium and water (+) have been strongly increased.

These observations reflect: the destruction of the plagioclase feldspars and the removal of the soluble constituents; the stability of the potassic feldspars (microcline); and the formation of hydrated clay minerals represented by sericite. The trace elements follow the major elements in pairs; Mn-Mg, Rb-K, and Sr-Ca.

Total Fe has been lost, suggesting that Fe_2O_3 has been converted to FeO and removed by leaching. Such reduction may have been caused by the exclusion of iron from the atmosphere by overlying material, or to an atmosphere deficient in oxygen.

As regolithic material contributed to the formation of the uraniferous, pyritiferous, oligomictic conglomerates of the basal Lower Huronian, the presence in the regolith of FeO (ferrous iron) and the persistence of uranium normally soluble in an oxidizing environment, is of interest, whatever the cause of reduction.

Roscoe and Steacy (1958, p.4 to 5) studied the distribution of uranium and thorium in two series of saprolite (regolith) samples from the Quirke Lake area of Buckles Township (formerly Township 144):

> "Both show uranium to be about one-third less in the most altered samples than in the freshest granite. One shows a proportional loss of thorium which is only slightly less than the loss of uranium. The other shows a net gain of thorium."

The source area for the uranium-bearing rocks was subjected to prolonged weathering with the development of residual regolith under reducing conditions. Slight topographic variation was developed in the terrain.

Proterozoic (Middle Precambrian)

HURONIAN SUPERGROUP

The Huronian Supergroup unconformably overlies the Archean Rocks. The classical descriptions of Huronian rocks were given by Logan (1863) and Collins (1925). Recent work has resulted in several revisions of Huronian

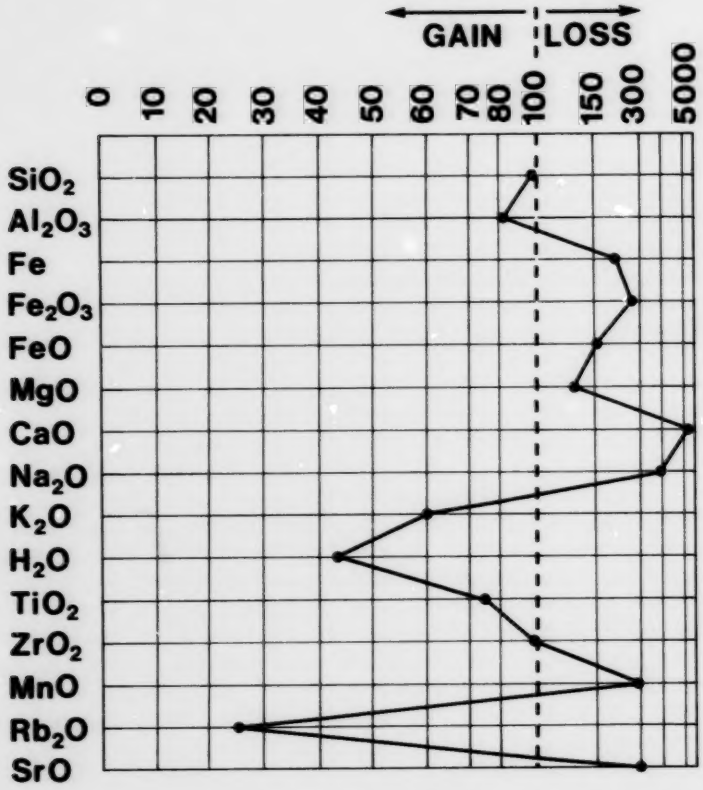

Figure 3 — Formation of regolith.

stratigraphy (J.A. Robertson *et al.* 1969) including the recognition of the cyclical nature of much of the sequence and the presence of mafic volcanic rocks near the base of the sequence at many localities (Roscoe 1969; J.A. Robertson 1971b).

Elliot Lake Group

The lowermost group of the Huronian Supergroup is the Elliot Lake Group, comprising the Matinenda and McKim Formations, and local mafic volcanic assemblages.

MATINENDA FORMATION

The Matinenda Formation consists of greenish arkose, with or without uraniferous quartz-pebble conglomerate beds, overlain by grey quartzite. Crossbedding and pebble orientation studies by McDowell (1957, 1963) and Pienaar (1963) indicate that the currents flowed from the northwest, but were markedly influenced by basement topography which, in turn, reflects the Archean structure. The ore-conglomerates occur mainly in valleys in the basement surface (Figure 7). The thickness of the Matinenda Formation increases from less than 0.3 m (1 foot) at the north shore of Quirke Lake through 180 m (600 feet) near Elliot Lake to 210 m (700 feet) on the north side of the Murray Fault at the Pronto Mine. Superimposed on the regional pattern are the effects of basement highs and lows. The formation has not been recognized south of the Murray Fault east of Algoma, but does lie under Lake Huron west of Blind River. Because northward overlap is pronounced (Figure 4) the ore-beds of the Nordic Zone are older than those of the Quirke Zone. If the northward overlap were not disrupted by basement highs, the ore-beds of the Pronto Zone, the most southerly known occurrence, would be the oldest, but in the absence of a regional marker layer this cannot be established. The quartz clasts at the Pronto Mine are cobbles, partly sorted and moderately rounded; of the Nordic they are large pebbles, well sorted and rounded; of the Quirke, they are small to medium sized pebbles, well sorted and rounded. Similar relationships were seen going up the sequence of both the Nordic and Quirke Zones and packing becomes less pronounced.

McKIM FORMATION

Argillaceous strata comprising the McKim Formation thicken southeasterly, and form the most important formation of the Elliot Lake Group on the southern limb of the Chiblow Anticline north of the Murray Fault between Shedden Township and the eastern limit of Figure 2 (J.A. Robertson 1965a; 1966a, b; 1975a). To the east of Algoma, this unit, but without any underlying arkose or Archean basement rocks, is repeated south of the Murray Fault. Near the fault, the McKim Formation is represented by schists having mineral assemblages characteristic of the

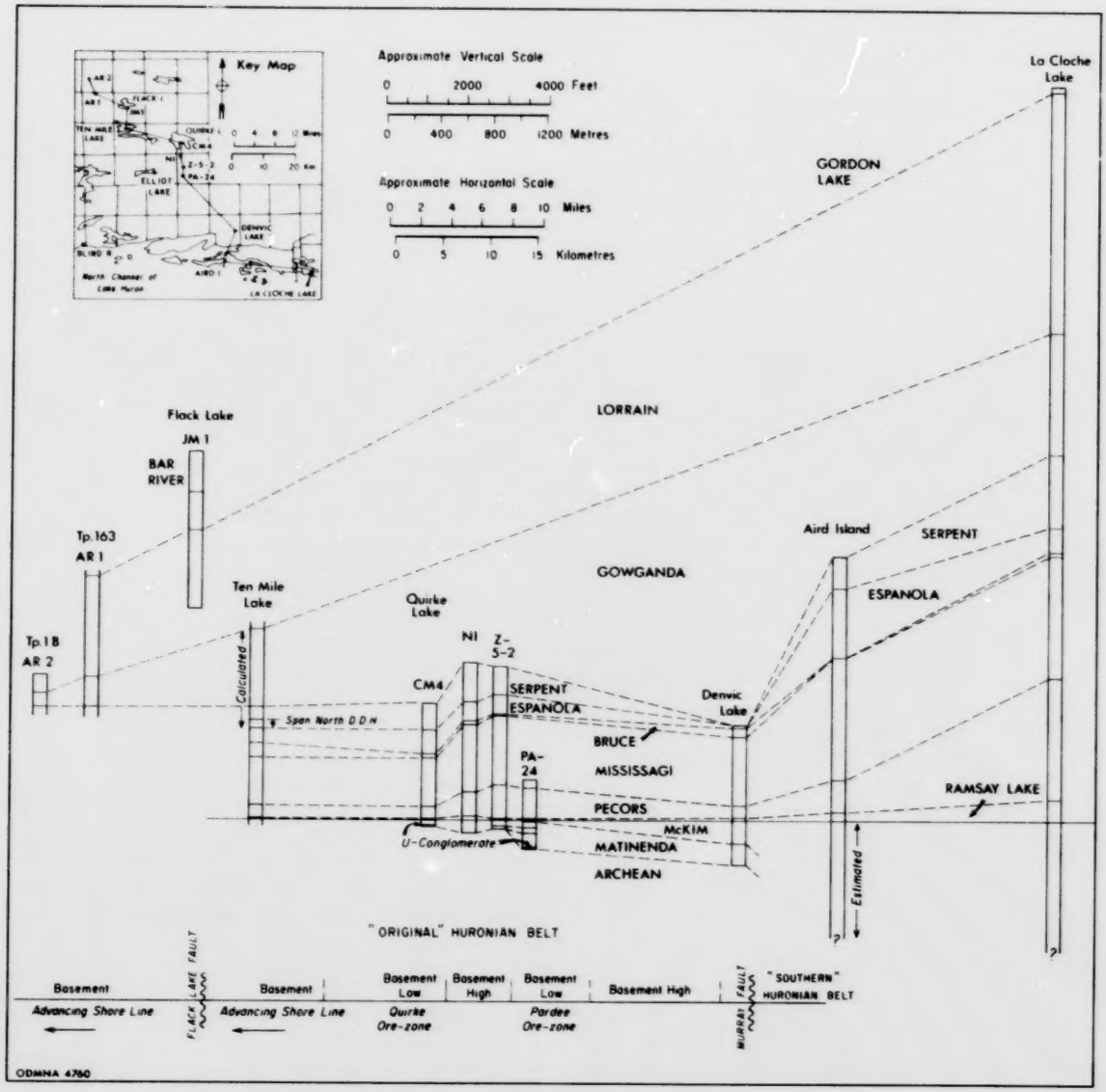

Figure 4 — Lateral variation of the Huronian Supergroup, Elliot Lake.

almandine-staurolite grade, but farther south it is represented only by poorly exposed less metamorphosed rocks (J.A. Robertson 1960, 1970a, 1976; Card *et al.* 1972). The unit south of the Murray Fault was formerly believed to be Archean in age (Collins 1925, 1936; Thomson 1962).

VOLCANIC ROCKS

In the Blind River area (Figure 2), mafic volcanic rocks are found at Thessalon, Dollyberry Lake, near the Nordic Mine, south of the Pronto Mine, and in the vicinity of Massey. Thick volcanic assemblages have also been recognized northeast of Sault Ste. Marie (Duncan and Aberdeen Townships) and between Agnew Lake and Sudbury. The rocks are characteristically massive, dark green to black, and only locally show feldspar phenocrysts and amygdules. Ropey structure and flow-top breccias have been recognized but pillows are very rare or absent, indicating subaerial environment. Pillows, however, have been observed in the upper part of the Duncan sequence (Bennett 1975) and in the Sudbury area (Innes 1975), possibly representing a transition to submarine deposition. Locally arkose and uranium-bearing, pyritic, quartz-pebble conglomerate are found, either interbedded in the fringe areas of the piles, or between the volcanic rocks and the Archean rocks (J.A. Robertson 1968b; Innes 1975; Bennett 1975). Locally at Thessalon and Massey, but better developed at Sudbury, intermediate and felsic flows are found. So far attempts to date these suggest a date of about 2,400 million years, but a reliable isochron needs to be established (Fairbairn *et al.* 1969). J.A. Robertson (1969a, 1976, p.73) has pointed out the close spatial relationships to two major fault zones, the Murray and the Flack which are also zones of marked changes in sedimentation style and thickness of individual stratigraphic units (see also Figure 4, this report).

Innes (1974, 1975) has studied the volcanic rocks at Sudbury. This data and limited work on the rocks at Massey (J.A. Robertson 1976) and Dollyberry Lake (J.A. Robertson, personal files) show the rocks are subalkaline tholeiities and contain iron and copper sulphide minerals. Between Massey and Sudbury layered gabbro-anorthosite intrusive bodies cut Archean rocks; these probably represent part of the same igneous cycle as the volcanic rocks and have similar chemical affinities. No age distinctions have been attempted.

The known uranium ore bodies are marginal to the volcanic piles that may have physically controlled the current which deposited the uraniferous conglomerates in the same way as the topographic highs reflect basement geology.

Emanations from the volcanism may also have contributed sulphur to convert detrital magnetite to pyrite in the sediments.

Hough Lake Group

The Hough Lake Group comprises the Ramsay Lake Formation, polymictic paraconglomerate; the Pecors Formation, argillite; and the Mississagi Formation, quartzite.

RAMSAY LAKE FORMATION

The Ramsay Lake conglomerate consists of pebbles and cobbles of grey granite, quartz, and mafic igneous rocks scattered in a dark grey greywacke to quartzite matrix characterized by large grains of smoky quartz and pyrite. The lithology indicates mass transportation, and an association with graded greywackes with dropped clasts suggests ice rather than mudflow as the transportation medium. A crude bedding particularly in the south, the presence of mudcracks and ripple marks on the upper surface of bedding planes and crossbedding in quartzite or greywacke lenses indicate deposition in shallow water.

On the north shore of Quirke Lake the Ramsay Lake Formation rests directly on basement (J.A. Robertson 1961, 1968a), but in the Quirke, Denison and Panel Mines it truncates the uraniferous beds of the Matinenda Formation and is itself slightly radioactive. Elsewhere, the Ramsay Lake Formation truncates arkose; the basal part of the formation is both lighter in colour and more potassic than the upper part, reflecting incorporation of material from the Matinenda Formation.

The Ramsay Lake Formation thickens from 0 to 4.6 m (0 to15 feet) at the northermost outcrops to over 300 m (1,000 feet) in the Espanola-Sudbury area (Card *et al.* 1972). The Ramsay Lake Formation indicates that the general climate was cold, and that the uranium mineralization was syngenetic.

PECORS FORMATION

The Ramsay Lake Formation is overlain conformably by the Pecors Formation, which comprises: a sequence of argillites in the Quirke Lake-Elliot Lake area; a sequence of argillites, siltstones and quartzites on the southern limb of the Chiblow Anticline and a sequence of siltstones and argillaceous quartzite where found south of the Murray Fault. The transition zone from the Ramsay Lake conglomerate comprises argillites which may include varvite with dropped clasts (J.A. Robertson 1968a), but locally a quartzite bed may be present. The argillites are frequently ripple marked. On the southern limb of the Chiblow Anticline and the southern limb of the Murray Fault, ripple marks, microcrossbedding and slumpage structures are characteristic.

The thickness ranges from 30 m (100 feet) at Quirke Lake (J.A. Robertson 1961, 1968a) to about 300 m (1,000 feet) south of the Murray Fault (J.A. Robertson 1976). The formation, however, may be missing over well-developed basement highs, and it is markedly reduced in thickness over the crest of the Chiblow Anticline. This reduction is in sedimentation thickness and not caused by folding. On the flank of a basement high running from Chiblow Lake to the Cutler-Massey area, some of the argillaceous beds of the Pecors Formation are moderately radioactive (J.A. Robertson 1975a, 1976, p.46).

MISSISSAGI FORMATION

The Mississagi Formation consists of greenish arkose on the northern limb of the Quirke Syncline. Elsewhere, it is normally formed of well-bedded grey quartzite, but adjacent to basement highs the yellow-green colour and increased feldspar content are again characteristic. Thicknesses range from 180 m (600 feet) at Quirke Lake to 460 m (1,500 feet) near Elliot Lake (J.A. Robertson 1961, 1968a) and to 820 m (2,700 feet) on the southern limb of the Chiblow Anticline, as exposed both north and south of the Murray Fault at Blind River (J.A. Robertson 1964). Current direction was from the northwest, but the influence of basement topography was much diminished.

Along the north limit of the Quirke Syncline, and again adjacent to the Chiblow-Cutler basement high, the yellow-green arkosic phase is characterized by radioactivity. Gamma-spectrometry reveals uranium and thorium as well as potassium (Darnley and Grasty 1971). In the northern section, thin pyritic quartz pebble bands, carrying sulphide and trace uranium and thorium mineralization, are found (J.A. Robertson 1963).

Quirke Lake Group

The Quirke Lake Group comprises: polymictic paraconglomerate of the Bruce Formation; carbonate and siltstone of the Espanola Formation; and quartzite of the Serpent Formation.

BRUCE FORMATION

The Mississagi Formation is overlain disconformably by the Bruce Formation, a conglomerate which consists of boulders of white granite and "greenstone" in a partly sorted, slightly pyritic, siliceous greywacke matrix. The Bruce Formation is probably a tillite that has been subjected to some sorting. Locally, dropped clasts have been seen (J.A. Robertson 1960, 1964) in varvite lenses. The conglomerate can be traced throughout the entire region. There are marked local variations in thickness, but north of the Murray Fault the unit is generally less than 60 m (200 feet) thick (Figure 4). South of the Murray Fault, the conglomerate is represented by a metre or so of conglomeratic grit. It is missing in places, and elsewhere, there are channels of boulder conglomerate up to several hundred feet in thickness.

The close similarity to the Ramsay Lake Formation should be noted (Figure 1). The matrix is more siliceous and is characterized by more pyrite, where metamorphosed this is replaced by pyrrhotite, and the formation has a magnetic expression which the present author identified by comparing regional geological and magnetic maps for the Espanola-Lake Panache Area, *cf.* Frarey and Cannon (1969) and MacLaren and Charbonneau (1968), and the lime and soda contents are greater than in the Ramsay Lake Formation. The basal part of the formation contains reworked material from the underlying Mississagi Formation.

ESPANOLA FORMATION

In the Blind River area the Espanola Formation consists of three units, (Figure 4): a lower unit, characterized by limestone, the Bruce limestone; a middle unit, characterized by mudstone and greywacke, the Espanola greywacke; and an upper unit having a marked development of ferruginous dolomite, the Espanola limestone. This three-fold division is not possible in the southeastern part of the area mapped, and the formation was not subdivided either north or south of the Murray Fault (Figure 4), (J.A. Robertson 1965a, b, c, 1966a) and (J.A. Robertson and McCrindle 1967). Near Espanola, an upper crossbedded quartzite member is present (Card 1976).

The Bruce limestone consists of thinly interbedded cream-coloured limestone and siltstone. Differential weathering and drag-folding give the rock a spectacular appearance. Where the unit is complete, the thickness is generally 30 m (100 feet).

The Espanola greywacke and Espanola limestone members can only be distinguished by the brown-weathering dolomite bands in the latter. Both members are characterized by intraformational breccias, siltstone and conglomerate dikes, mudcracks, and ripple marks. These indicate shallow-water deposition and tectonic disturbance. Occasional quartzite beds, which become more common to the northwest, show crossbedding that is indicative of a northwesterly derivation. Where the section is complete in the Quirke Syncline, the thickness of the Espanola greywacke is 90 to 120 m (300 to 400 feet) and that of the Espanola limestone is 46 m (150 feet).

The Espanola Formation is of considerable interest because it represents an early carbonate. The presence of carbonate and of iron suggests that the environment contained some free oxygen.

SERPENT FORMATION

The Espanola Formation is overlain by the Serpent Formation, a white feldspathic quartzite, which is best exposed in the northern and eastern sections of the Quirke Syncline. The maximum known thickness of the Serpent Formation is 340 m (1,100 feet). Crossbedding, and lithology and thickness changes in individual members, again indicate a derivation from the northwest. Ripple marks and mudcracks indicate shallow-water conditions. The unit is also exposed in Shedden Township north of Walford Lake, and on islands in the North Channel of Lake Huron at the south limit of the area mapped (Figure 3), (J.A. Robertson 1965a, b, c, 1966a, 1975b, c) and (J.A. Robertson and McCrindle 1967).

Cobalt Group

The Quirke Lake Group is followed unconformably by the Cobalt Group, which, in the Blind River-Elliot Lake area, consists of the Gowganda Formation and the Lorrain Formation, the Gordon Lake Formation and the Bar River Formation.

GOWGANDA FORMATION

Within the map-area (Figure 2), the Gowganda Formation rests on all formations between the Upper Mississagi and the Serpent Formation; in the Mount Lake and Kirkpatrick Lake area, north of the Flack Lake Faults (J.A. Robertson 1971b; Siemiatkowska and Guthrie 1975), it rests on the Archean basement. Locally, the contact can be seen truncating the bedding of the underlying formations, and consolidated or partly consolidated fragments of the underlying rocks are found in the lowermost beds of the Gowganda Formation; elsewhere, the contact is a "soft-sediment" contact, and in yet other localities it is a knife-sharp contact.

The Gowganda Formation is a heterogeneous assemblage of conglomerate, greywacke, quartzite, and argillite. These rock types are found throughout the sequence, although the lower part is characterized by boulder conglomerate in which red granitic clasts predominate and the upper part by quartzite and argillite. Within the Quirke Syncline, as mapped by the writer, the Gowganda Formation is about 520 m (1,700 feet) thick (J.A. Robertson 1963). To the west, in areas mapped by Frarey (1959, 1962), it is at least 900 m (3,000 feet) thick. To the north near Mount Lake, the formation lies on basement rocks and is less than 150 m (500 feet) thick (Wood 1968a, b; 1975). To the south, in the La Cloche Syncline, the Gowganda Formation is some 1,280 m (4,200 feet) thick (J.A. Robertson and McCrindel 1967), at La Cloche Lake and in the Willisville-Espanola area (Casshyap 1966, 1968). The conglomerate matrix is fine-grained, chloritic, and characterized by high soda content relative to the lower Huronian polymictic conglomerate (Figure 5).

The origin of the Gowganda Formation has been much discussed. Dense boulder conglomerates, quartzites and argillites were definitely waterlaid; varved conglomerates and greywackes probably formed under conditions characterized by alternate freezing and thawing, although some authorities would ascribe these rocks to turbidity currents; and sparse boulder conglomerates with a disrupted greywacke matrix may be either tillites or mudflow deposits. Ovenshine (1964, 1965) has described the structures of the Gowganda Formation of the Elliot Lake-Blind River area, and has endorsed a glacial environment, particularly on the basis of numerous dropped clasts in varved greywackes. In the southeastern part of the area shown in Figure 2, and in the areas to the east mapped by Card (1967a, b, c, d) and Casshyap (1966, 1968), a marine rather than a continental glacial environment is indicated (see also Lindsey 1966). Some clasts are striated, but Robertson (1971a) has questioned the use of this feature as a criterion for glacial action (Lindsey *et al.* 1970), and suggests that it is caused by post-depositional tectonism *cf.* Bielenstein and Eisbacher (1969). Of particular interest is the presence of iron oxide in the Gowganda Formation. The quartzites are red to pink in colour reflecting the preservation of hematitic dust in the feldspar and interstitial material. Some thicker beds of argillite or siltstone contain magnetite and zones of such material can be traced on regional magnetic maps, for example see Robertson (1963, Map No. 2015), (1976, p.64), and page 15 of this report. No significant uranium anomalies have been identified, but scattered thorium-potassium values (Richardson *et al.* 1975) reflect the granitic content of the conglomeratic lower portion of the formation.

The lack of a preserved regolith at the Archean surface (J.A. Robertson 1970c; Wood 1970a) may indicate oxidizing rather than the reducing conditions that prevailed during the deposition of the Lower Huronian sediments elsewhere in the district (J.A. Robertson 1969a; Roscoe 1969; Wood 1970a).

LORRAIN FORMATION

The Lorrain Formation conformably overlies the Gowganda Formation. In the Flack Lake area several units have been mapped within the Lorrain Formation in the following ascending stratigraphic order: 1) pink ferruginous quartzite and minor siltstone; 2) coarse-grained green arkose; 3) pink coarse hematitic arkose with radioactive (thorium:uranium > 10:1) quartz-pebble conglomerate (J.A. Robertson 1970c; J.A. Robertson and Johnson 1970); 4) interbedded pink and buff quartzite and in a few places, greenish quartzite (quartz-chert-jasper pebbles bands are characteristic of the upper part of this member); 5) massive white quartzite, with quartz-chert-jasper pebble bands in the lower part. Sericite, kaolinite, pyrophyllite, and diaspore are found in the non-feldspathic beds, Members 4 and 5 (Chandler *et al.* 1969) and indicate the onset of warm, rather than frigid conditions (Wood 1970a; Young 1970). Crossbedding is common in the Lorrain Formation in the Flack Lake-Mount Lake-Rawhide Lake area but is variable; southwesterly current directions have been interpreted by Hadley (1969) and the writer (field notes), although the source area was probably to the north. North of Bruce Mines, Hadley (1969) deduced southeasterly current directions. The five members can be traced throughout the Flack Lake-Mount Lake-Rawhide Lake area (J.A. Robertson 1971b; Wood 1975; Siemiatkowska and Guthrie 1975). Their equivalents can also be recognized and traced in the La Cloche Lake-Whitefish Falls area (Card 1971; Chandler 1969) but the individual units are both finer grained and thicker indicating deposition farther from source. They have been strongly folded, foliated, and somewhat metamorphosed; the clay minerals are represented by kyanite and andalusite (Church 1967; Chandler 1969; J.A. Robertson 1970b, 1976).

GORDON LAKE FORMATION

The Lorrain Formation is overlain, apparently conformably, by the Gordon Lake Formation, a 300-m (1,000 foot) thick sequence of well-bedded siltstone, argillite chertstone, and fine- to medium-grained sandstone. There are three members: 1) a lower member comprising reddish sandstone and siltstone with anhydrite and gypsum nodules (and salt casts?); 2) a middle member of dark green siltstone, argillite, and minor sandstone; and 3) an upper member of reddish siltstone, argillite, and chert (Eisbacher and Bielenstein 1969; Bottrill 1970; J.A. Robertson 1969b, 1970c). The middle member tends to form a scarp in the Flack Lake area that corresponds to a moderate magnetic anomaly (J.A. Robertson 1971b). This magnetic anomaly is shown on Keevil Mining Group Limited, drawing number 3798 (Assessment Files Research Office, Ontario Division of Mines, Toronto). Current ripples, microcrossbedding, slumpage structures, and

desiccation cracks indicate deposition in very shallow water (Young 1969; J.A. Robertson 1969b; J.A. Robertson and Johnson 1969; J.A. Robertson 1970c; J.A. Robertson and Johnson 1970; Wood 1970a, b). A few tens of metres of siltstone and quartzite in the core of the La Cloche Syncline which have been correlated with the Gordon Lake Formation also coincide with a magnetic anomaly (J.A. Robertson 1976, p.72).

BAR RIVER FORMATION

The Gordon Lake Formation is overlain by the Bar River Formation, which comprises at least 370 to 460 m (1,200 to 1,500 feet) of massive to well-bedded orthoquartzite, generally crossbedded and ripple marked (J.A. Robertson 1969c; J.A. Robertson and Johnson 1969; Woodward 1970; Eisbacher and Bielenstein 1969). Mudcracks and desiccation features are also found, particularly in finer grained sandstone and intercalated siltstone bands. One unit is characterized by thin bedding and ferruginous siltstone and quartzite. The iron has been partly redistributed, and small-scale solution depositional fronts adjacent to joints and fractures are common. Some ripple marked surfaces at this horizon are covered with segmented, tapering, sinuous structures of possible organic origin (Hoffman 1967; Young 1967; Donaldson 1967). Young (1967) and Hoffman (1967) favoured metazoans (worms) as the organism involved, but Donaldson (1967) suggested that the structure represents the infilling of desiccation cracks in algal mats. In the same area there are many similar structures that are undoubtedly desiccation features. The desiccation features of the Gordon Lake Formation (Young 1969; J.A. Robertson 1969b) are so similar to the most organic-looking structures of the Bar River Formation that the organic nature of the latter remains in doubt. Wood (1970a, b) has recorded oolites in the ferruginous rocks, and their presence along with the primary structures, indicates deposition in very shallow water. In the ferruginous rocks Bottrill (1970, personal communication) has observed pyrite and in polished section has identified the major iron mineral as maghemite rather than hematite. The conditions of deposition, sedimentation, climate, and state of atmospheric oxidation represented by the upper Huronian rocks of the Flack Lake have been discussed in more detail by Wood (1971).

Summary of Huronian

The Huronian rocks of the Southern Province thus comprise thick sequences of clastic sedimentary rocks and minor tholeiitic basalts as shown in Table 3. The sedimentary rocks were derived from the adjacent Archean craton, and were deposited as migrating diachronous facies with cyclical rejuvenation. The depositional basin extended east-west, and deepened towards the southeast. The distribution of volcanic rocks and a marked change in thickness and facies of sedimentary units were controlled by hinge zones which later became regional fault zones. Minor changes in composition of similar rock types are due to shifts in provenance and to the efficacy of weathering, and winnowing processes. Radioactivity and

TABLE 3 | SUMMARY OF HURONIAN STRATIGRAPHY IN THE BLIND RIVER-ELLIOT LAKE AREA

Group	Formation	Lithology	Thickness (in feet)[1]	Depositional Environment	Source	Mineralization
Cobalt	Bar River	Quartzite	At least 1,000-Flack Lake; at least 4,000-Willisville	Shallow water	Source north but currents variable	
	Gordon Lake	Siltstone, sandstone	1,000-Flack Lake; 3,000-Willisville	Shallow water		
	Lorrain	Quartzite, conglomerate, arkose	2,000-6,000	Shallow water	North-northwest	Th-U in north Cu?
	Gowganda	Conglomerate, greywacke, quartzite, siltstone	500-4,200	Glacial in north; glacial-marine in south	North-	
Quirke Lake	Serpent	Quartzite	0-1,100	Shallow water	Northwest	
	Espanola	Limestone, dolostone, siltstone	0-1,500	Shallow water	Northwest	U trace in Victoria Tp. Cu in limestone against diabase
	Bruce	Conglomerate	0-200	Glacial-shallow water	North?	
Hough Lake	Mississagi	Quartzite	0-3,000+	Shallow water	West-northwest in west; north in southeast	U near basement highs
	Pecors	Argillite	40-1,000+	Shallow water	North-northwest	Traces U near basement highs
	Ramsay Lake	Conglomerate	5-200	Glacial-shallow water	Northwest?	Traces U where unconformable on Matinenda Formation
Elliot Lake	McKim	Argillite-greywacke	0-2,500+	Shallow water (turbidite)	Northwest	Traces U near basement highs
	Matinenda	Quartzite, arkose, conglomerate	0-700+	Shallow water	Northwest	U-Th-Rare Earths in conglomerate in basement lows*
	Volcanic rocks	Andesite-basalt (felsic volcanic rocks)	Local piles	Subaerial	Flack Lake F. Murray F.	U-Th in conglomerate interbeds

*All U-deposits of commercial importance in the Blind River-Elliot Lake area are in the Matinenda Formation.

Footnote
[1] To convert to metres, multiply by 0.30

Abbreviations
Cu - Copper
Th - Thorium
U - Uranium

heavy minerals are characteristic of quartz-pebble conglomerate in the fluviatile near shore facies. In the lower Huronian, the association is of uranium and sulphide minerals, predominantly pyrite, and in the upper Huronian it is of thorium and iron oxides as shown in Table 3. In the middle Huronian, conditions became favourable for preservation of iron oxides. Glacial deposits are characteristic of the lower and middle Huronian, whilst the uppermost Huronian was apparently deposited in a dry and hot environment. Figure 5 illustrates the alkali contents of the polymictic paraconglomerate, in Figure 6, various ratios for the argillaceous rocks are shown. Of particular interest in Figure 5 is the variation in maturity of the paraconglomerate matrixes which decreases towards the Gowganda Formation, the marked increase in soda, and, in the lower part of the paraconglomerate sequences, the incorporation of potassic material from the underlying arenite. Figure 6 shows the increase in ferric iron to ferrous iron in the argillaceous rocks, reflecting change in general oxidation conditions, the increase in SiO_2/Al_2O_3 ratio reflecting increased efficacy of chemical weathering in the upper Huronian, and variations in Na_2O/K_2O ratio reflecting changes in provenance from granitic rocks "greenstone". The arenaceous rocks show similar changes in provenance and efficacy of chemical weathering. The role of oxidation is apparent in the frequency of red beds from the Gowganda Formation upwards contrasted to the total lack of red beds in the lower formations.

POST-HURONIAN EVENTS

Closely following sedimentation, the area was subjected to a long history of structural deformation, igneous intrusion, and, in the Penokean Fold Belt to regional metamorphism, which locally attained amphibolite facies (Card 1964; Card *et al.* 1972; J.A. Robertson 1972). These events do not concern the formation of the uranium deposits. The oldest intrusion, the Nipissing Diabase, took place at 2,155 ± 80 million years (Van Schmus 1965) and this serves to place a minimum age on the Huronian sedimentary rocks. Alteration (albitization, chloritization, and carbonatization) associated with dikes or sills has locally affected the uranium deposits which were clearly in place before the intrusion (J.A. Robertson 1968a, 1970a).

In general, the deformation and metamorphism of that part of the Blind River area in which uranium ores are found is minimal. The lack of intense metamorphism may be regarded as a factor in preservation of the ore bodies. Age data on minerals, however, reflect some resetting of the decay clocks that at times correspond to known peaks of regional metamorphism or thermal events, rather than episodic introduction of further uranium (Roscoe 1969).

THE URANIUM DEPOSITS

Uranium and thorium uranium deposits are found in conglomerates at a number of localities in the Blind River-Elliot Lake and Agnew Lake areas as well as at intervals throughout the Huronian Belt (J.A. Robertson 1968a, 1975a; Thompson 1960).

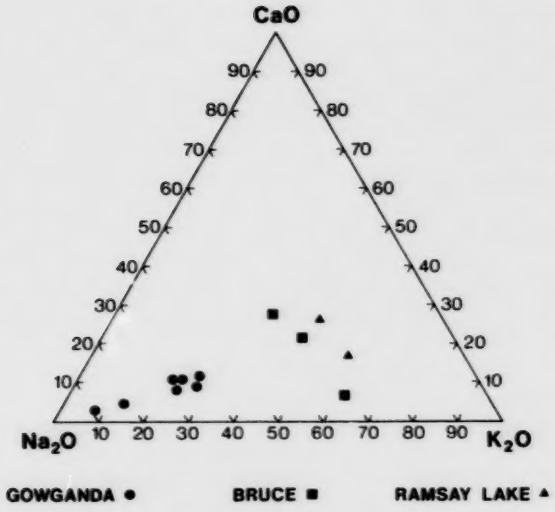

Figure 5 — Alkali content, Huronian polymictic conglomerates.

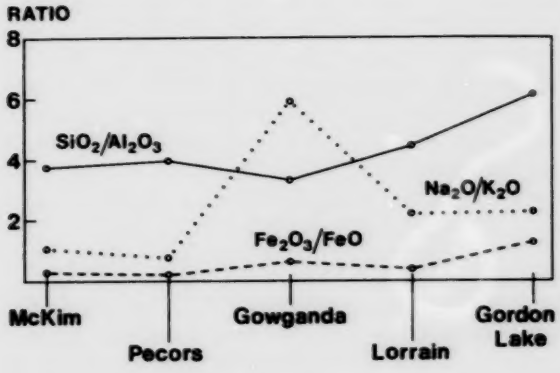

Figure 6 — Silica/Alumina, Ferric Iron/Ferrous Iron, Soda/Potash ratios for Huronian argillaceous rocks.

DISTRIBUTION OF URANIUM ORE DEPOSITS – BLIND RIVER-ELLIOT LAKE

The workable uranium deposits of the Blind River Camp are found (Figure 7) as quartz-pebble pyritic conglomerate beds in zones controlled by basement topography. In the Quirke Syncline, the relationship of the uraniferous conglomerate beds to granite-"greenstone" contact areas, and valleys over softer zones in the greenstone belt is clearly demonstrated (Figure 7). At Pronto, however, there is no clear relationship to basement geology, which raises the possibility that there may be other economic uranium deposits underlain by granite. It is, however, clear that the deposit is located on the flank of a regional basement high.

The ore zones strike northwest-southeast, and are controlled by basement structures. The Quirke Zone (the largest in the area) is 9,700 m (32,000 feet) long and from 1,800 to 2,700 m (6,000 to 9,000 feet) wide and the Nordic Zone is 5,800 m (19,000 feet) long and from 1,340 to 1,800 m (4,400 to 6,000 feet) wide (J.A. Robertson 1967, 1968b). The Pronto Deposit (J.A. Robertson 1970a) and the unworked zones are of smaller dimensions.

At Quirke No. 1 Mine the main ore zone is approximately 30 m (100 feet) above basement and is approximately 3.5 m (12 feet) thick. Towards the east, this bed is truncated by an unconformity at the base of the Ramsay Lake conglomerate.

At Quirke No. 2 Mine and the Denison Mine, the best ore development is in the Denison Reef some 30 m (100 feet) below the Quirke Reef. The Denison Reef normally comprises two conglomerate zones each 1.8 to 3.6 m (6 to 12 feet) thick separated by barren arkose 0.6 to 2.4 m (2 to 8 feet) thick. Throughout much of the Denison Mine, ore grade was sufficient to permit mining of both conglomerate beds and the intervening quartzite as one unit using large-scale equipment and trackless haulage. Quirke No. 2 Mine has been developed using conventional haulage. Other conglomerate beds 0.6 to 3 m (2 to 10 feet) thick, separated by quartzite beds 3.6 to 6 m (12 to 20 feet) thick, are known on both the Quirke and Denison properties, but these have not been mined. At Stanrock Mine another reef was found under the Denison Reef in the southeastern part of the mine. The *en-echelon* pattern with the oldest reef to the southeast conforms to the regional overlap pattern. The nomenclatures used in the various mines of the Quirke Zone, and the stratigraphic relationships are illustrated schematically in Figure 9.

At the Nordic Mine, the main ore-bed comprises conglomerate or conglomerate with quartzite over a width of 3 m (10 feet), and with a grade of 2.5 lbs. U_3O_8 per short ton. Locally, another reef lower in the sequence, the Lacnor Reef, was mined where grade attained 2.0 lbs. U_3O_8 per short ton. In the eastern part of the mine a third reef, the Pardee Reef, attains ore grade (2.3 lbs. U_3O_8 per short ton over 1.5 m [5 feet]). This reef extends eastward over a basement ridge into the Pardee and Pecors mineralized zones (Figure 7). These reefs extend down rake to the Stanleigh Mine. Operations were largely carried out in the Lacnor and Nordic Reefs. As with the Quirke Zone, other reefs of conglomerate of sub-marginal grade or poor extent are known.

Five types of boundary to the ore beds are known:

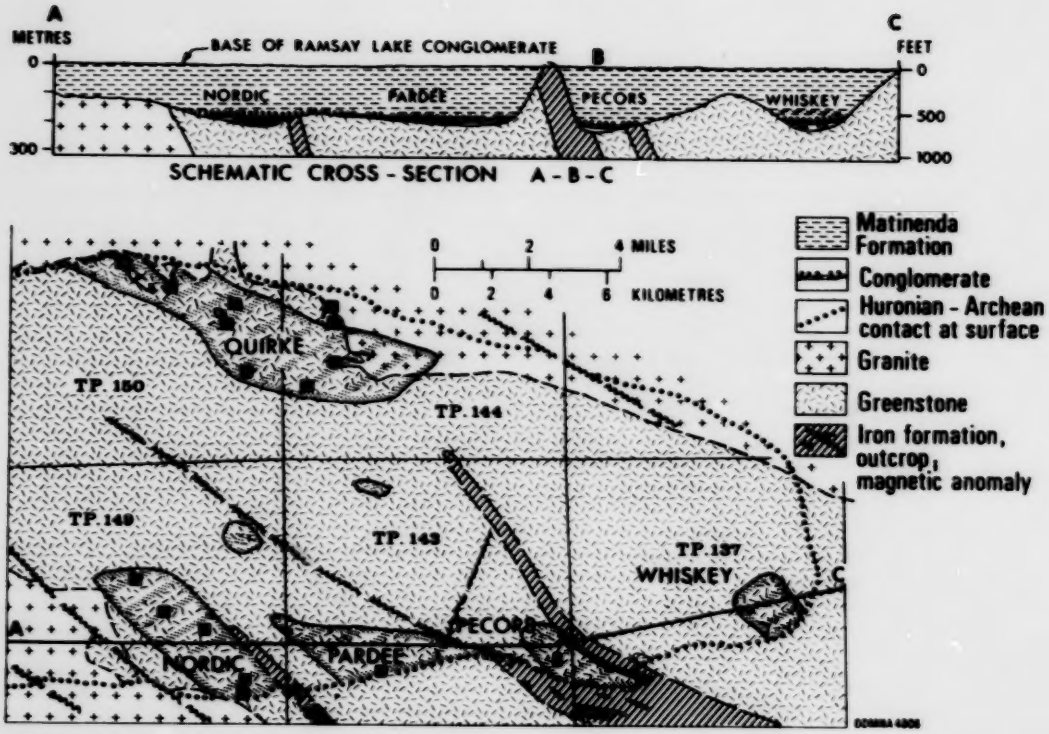

Figure 7 — Uranium deposits in Quirke Syncline.

Figure 8 — Cross-section New Quirke Mine.

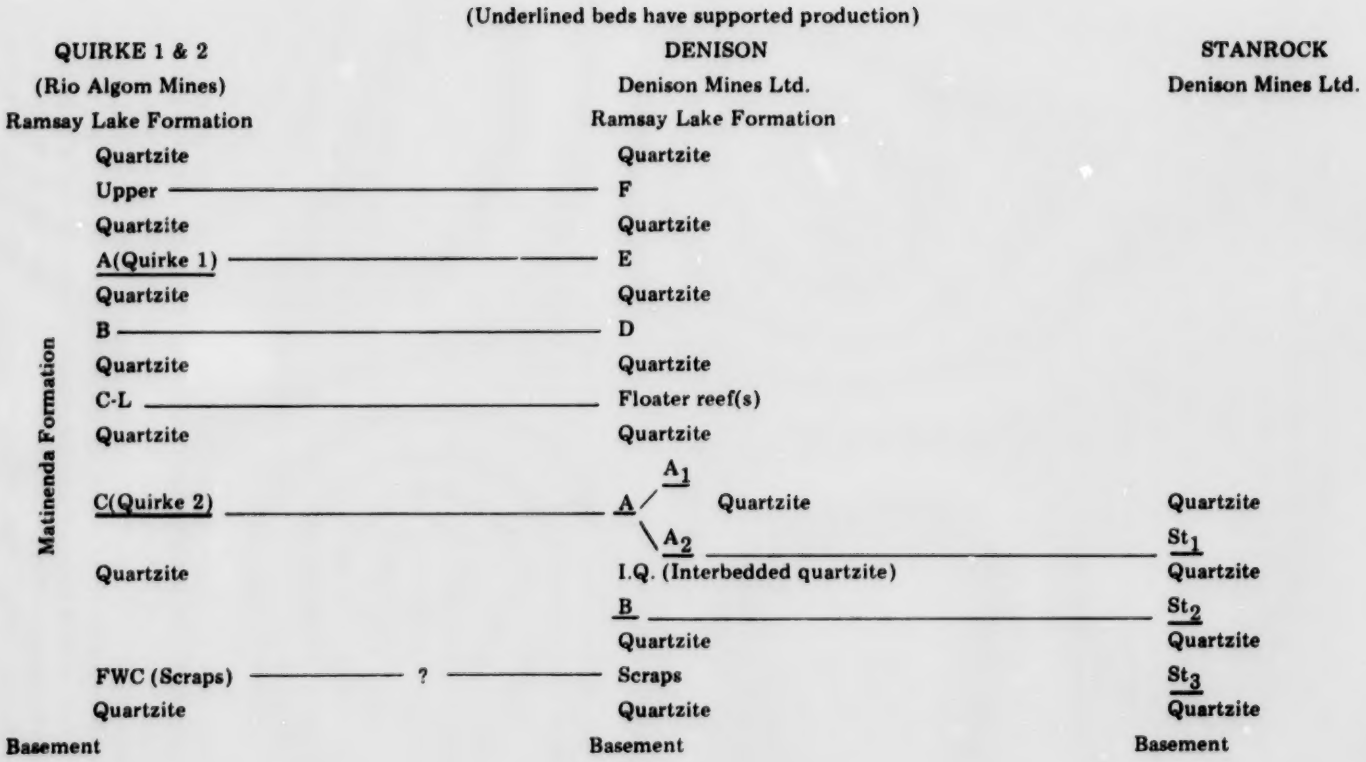

Figure 9 — Correlation of quartz-pebble conglomerate reefs, Quirke Zone.

1. Outcrop of the conglomerate bed.
2. Wedging owing to contact with basement surface, either regional or local "highs". To the west of Quirke No. 1 Mine the "basement" may be the edge of a pile of Huronian volcanic rocks rather than Archean volcanic rocks.
3. Lateral thinning of conglomerate and thickening of the intervening quartzite beds accompanied by drop in grade of the radioactive units. This is probably the typical boundary and the definition is arbitrary.
4. Removal of conglomerate by erosion subsequent to deposition, as for example in Quirke, Denison, and Panel Mines, where there is an unconformity at the base of the Ramsay Lake conglomerate. Where material from conglomerates of the Matinenda Formation has been incorporated in the Ramsay Lake conglomerate, the latter contains anomalous, but minor amounts of uranium radioactivity in Ramsay Lake conglomerate.
5. Faulting. Locally, areas were not mined either because of unfavourable mining conditions caused by faults, extensive fracturing, diabase dikes or unfavourable milling conditions caused by albite, chlorite, or carbonate alteration.

Some of these relationships are illustrated in Figure 8, a cross-section through the Quirke No. 2 Mine of Rio Algom Mines Ltd.

LITHOLOGY AND MINERALOGY OF URANIUM ORE DEPOSITS

The typical ore-bearing conglomerates of the Matinenda Formation consist of well-rounded, well-sorted, quartz pebbles in a matrix of quartz, feldspar, and sericite, and have an average pyrite content of 15 percent. Monazite and zircon are characteristic heavy minerals. Brannerite and uraninite are found in the matrix. The ore minerals are brannerite, uraninite, and monazite (J.A. Robertson 1960 *et seq.*; Roscoe 1957 *et seq.*; Pienaar 1963; Roscoe and Steacy 1958).

Thucholite is present in the ore, but is also in fractures as a post-ore secondary mineral. Whilst the presence of "thucholite" or radioactive hydrocarbon has been noted in the Blind River camp, until recently comparatively little attention has been paid to it. However, the work of Pretorius (1975), Hallbauer (1975) and others in South Africa led Ruzicka to discuss the Elliot Lake hydrocarbon (as found in the ore beds) at the Denver Workshop (see Ruzicka and Steacy 1976, p.343-346). Ruzicka suggested a biogenic origin for that variety of hydrocarbon. A furtner discussion of Elliot Lake Thucholite by Kaimain and Wood at the 1976 GAC Convention in Edmonton concentrated on the globular variety found on open surfaces at the Milliken Mine; these authors suggested that such thucholite formed as a result of the radioactive polymerisation of diesel fumes from mining equipment. Gummites (soddyite and uranophane) are rare, but Rice (1958) stated that they form a significant proportion of the ore mineralization at the Spanish American Mine. Uranothorite has also been identified (Roscoe and Steacy 1958, p.14). Patchett (1959, 1960) identified coffinite in altered material from the Nordic Mine. Pyrite is

the most common sulphide mineral; it usually constitutes 10 to 15 percent of the matrix, but rarely it may be as high as 30 percent. Pyrite is concentrated in the matrix, and only rarely is there an indication of replacement or fracture-filling in the quartz pebbles. Individual grains may be rounded ("buckshot" pyrite) or subhedral to massive. R.G. Arnold (1954) suggested that the pyrite was formed by sulphidization of detrital magnetite, and he described grains showing cores rich in leucoxene that he considered to have developed from ilmenite exsolved from the original magnetite.

More recently, Bottrill (1971) has suggested that the sulphur required was derived from the lower Huronian volcanic rocks. However, no laboratory studies have been undertaken to test this hypothesis.

Pienaar (1963) in a trace-element study could not distinguish between the pyrite of the ore beds and the pyrite found in the other rocks of the district. Other sulphide minerals found are: pyrrhotite (occasional scalenohedral pyrrhotite crystals have been found in vuggy cavities); chalcopyrite, and minor arsenopyrite; galena (probably radiogenic); cobaltite; and marcasite, molybdenite, and sphalerite as coatings in late fractures (often with thucholite). At the Denison Mine, tourmaline crystals were observed in a late quartz veinlet (R. Gunning, personal communication, 1963). The following heavy detrital minerals have also been identified; anatase, amphibole, barite, apatite, cassiterite, chromite, diopside, garnet, epidote (allanite?), gold, fluorite, hematite, ilmenite, magnetite, monazite, rutile, scheelite, sphene, spinel, tourmaline, xenotime, yttrofluorite, and zircon (malacon and more rarely cyrtolite)(Abraham 1953; Arnold 1954; Holmes 1956, p.126; Milne 1959; Patchett 1960; Pienaar 1958, 1963; Ramdohr 1957, 1958a, 1958b; Rice 1958; Roscoe 1957; Roscoe and Steacy 1958, p.13-15; Thorpe 1963; and CIMM 1957).

In addition Milne (1959) in samples collected for Patchett (1960) at the Nordic Mine identified chamosite, greenalite, and grunerite. These iron silicates were probably derived from the ridge of iron formation forming the eastern boundary of the Nordic Channel (see Figure 7).

Although a wide variety of detrital minerals have been identified and described by the authors listed above, it should be stressed that these occur in very small quantities and are not present in all samples that have been studied.

There has been much discussion and description of the main minerals in the ore; mainly from polished section work. The similarity to the gold and uranium-bearing bankets of the Witwatersrand (Ramdohr 1958a, b; Pretorius 1975), radioactive conglomerate at Jacobina in Brazil (Bateman 1958; Gross 1968), Rum Jungle in Australia, and possibly some deposits of uncertain age in Russia (Ruzicka 1971, p.61) has been stressed in the literature (Davidson 1957; Derry 1960).

The major ore mineral at the Pronto Mine and at the A reef Quirke Mine (Theis 1973) is brannerite, first described from the area by Nuffield (1954, p.520-522). Although some relatively fresh material has been observed (Rice 1958), brannerite is typically found as ovoid red-brown to black grains in the metamict state, showing bladed rutile surrounded by a uranium oxide and rare-earth oxides, the two-phase uranium titanium compound of Pienaar (1958, 1963). Pienaar (1958, 1963), Roscoe (1969), D. Robertson and Steenland (1960) suggest that the rounding is caused by

TABLE 4 URANIUM, THORIUM, AND TITANIUM CONTENTS OF BLIND RIVER BRANNERITE AFTER J.A. ROBERTSON (1968a, p.92).

MINE	AUTHOR	COLOUR	COMMENTS	U_3O_8	ThO_2	TiO_2	U_3O_8/ThO_2
				percent	percent	percent	
Others than Blind River	Thorpe (1963)	.....	.....	40-52	0.3-9.15	32-40	40-52
Nordic	Patchett (1960)	reddish brown	altered	32.6	2.6	30.3	12.5
Nordic	Patchett (1960)	darker	more glassy, less altered	32.2	1.8	30.5	17.9
Denison	Roscoe (1959a)	black	.....	41	6.1	20	6.7
Denison	Roscoe (1959a)	dark brown	.....	36	1.8	30	20.0
Quirke	Roscoe (1959a)	dark brown	.....	24	1.7	37	14
Quirke	Roscoe (1959a)	brown	.....	20	2.2	30	9.1
Quirke	Roscoe (1959a)	cream	.....	6	1.2	27	5.0
Can-Met	Pienaar (1963)	veinlet material	.....	8.70	1.14	n.d.	7.6
Regional	Thorpe (1963)	.....	.....	30	2.3	30	13

TABLE 5 | URANIUM AND THORIUM CONTENTS IN BLIND RIVER URANINITE, AFTER J.A. ROBERTSON (1968a, p.93).

MINE	AUTHOR	U_3O_8 percent	ThO_2 percent	U_3O_8/ThO_2
Denison	Pienaar (1963)	48.4	5.6	8.65
Denison	Pienaar (1963)	39.0	7.2	5.4
Denison	Pienaar (1963)	55.5	5.4	10.3
Nordic	Patchett (1960)	55.25	6.25	8.85
Quirke	Wanless and Traill (1956)	51.7	4.1	12.6
Pronto	Wanless and Traill (1956)	57.0	5.12	11.1
Nordic	Roscoe (1959a)	64	6.3	10.15
Denison	Roscoe (1959a)	60	5.9	10.2
Panel	Thorpe (1963)	29.6[1]	3.84[1]	7.7[1]
Regional	Thorpe (1963)	60	6	10

[1] Contaminated?

TABLE 6 | ANALYSES OF BLIND RIVER MONAZITES, AFTER J.A. ROBERTSON (1968a, p.93).

	ROSCOE (1959b)				THORPE (1963)	
	1	2	3	4	Range	Average
Colour	orange	yellow	grey	grey		
ThO_2	5.9	3.9	6.7	5.9	5.6-6.2	5.6
U_3O_8	0.31	0.95	1.65	2.9	1-2	1.4
U_3O_8/ThO_2	0.0525	0.244	0.246	0.492	0.18-0.32	0.25

transportation and that the material is detrital. Ramdohr (1957) has suggested that the brannerite, rather than decomposing, is synthetic, and has proposed the "Pronto Reaction" $UO_2 + 2\text{-}3TiO_2 = UTiO_{2\text{-}3}O_{6\text{-}8}$ which he held took place during metamorphism. Experimental efforts to reproduce this reaction indicate that it takes place at temperatures in excess of those to which the rock has been subjected (Gruner 1959, p.1,315; Patchett 1959). The mineral generally contains small inclusions of pyrrhotite and of radiogenic galena (Thorpe 1963, p.39). Table 4 lists the published partial analyses of brannerite from the Blind River area along with the regional value selected by Thorpe.

Blind River brannerite has been recently studied by Ferris and Rudd (1971) and by Theis (1973).

These authors concluded that the Blind River brannerite (and the brannerite or uraniferous leucoxene of the Rand) formed at low temperatures during diagenesis as a result of uranium migrating to decomposing ilmenite.

Uraninite is the second most important mineral at the Pronto Mine, and apparently the most important in the Nordic Zone and in the C Reef at the Quirke Mine (Theis 1973). Generally it occurs as black subhedral grains approximately 1 mm across. Ramdohr (1958a, b) and D.S. Robertson (1962a, 1962b, 1974) have described rounded grains. Derry (1960) and Thorpe (1963) have both selected 6 percent as the regional value of ThO_2 content. Table 5 summarizes the early published data on Blind River uraninite since confirmed by Grandstaff (1974), repeated at the Golden workshop. This corresponds to the composition of pegmatitic rather than hydrothermal uraninite. The rounding and thorium content may indicate a detrital origin. Rice (1958) however believes that uraninite formed as a result of leaching from brannerite by hydrothermal solutions emanating from diabase (which is more common in the Nordic Mine than elsewhere). Patchett (1960) also supports a secondary origin for uraninite and stated that the cores are carbon-rich. Davidson (1957, 1965) has used the general lack of uraninite in modern placers and geochemical principles along with the Lyellian concept of uniformitarianism (actualism) as an argument against the detrital origin of uraninite.

Roscoe (1959a) has described the monazites from the Blind River ores and has pointed out that monazite can contain considerable uranium and is, therefore, one of the ore minerals.

Grains are normally rounded to subangular, and less than 0.3 mm in diameter. Grey varieties are strongly radioactive, may contain uranothorite or thorite (Roscoe 1959b; Patchett 1959), and have pyrite inclusions. Table 6 gives Roscoe's (1959b) uranium-thorium analyses of monazites and the values selected by Thorpe (1963).

Almost no work has been done on thucholite at Blind River-Elliot Lake. The recent interest in hydrocarbon at the Rand has prompted Ruzicka and Steacy (1976) to initiate comparative studies on Blind River material, (see also page 26 this report).

Roscoe (1959a, b) has shown that the uranium-thorium ratios are comparable to that of the basement. The lateral variation in the ore-mineral and uranium-thorium ratios as studied by Roscoe (1959a, b), D. Robertson (1962a, b, 1974), J.A. Robertson (1968a) and Thorpe (1963) are best explained by the relative stability of monazite during transportation; monazite is the chief radioactive mineral in the occurrences in the Lorrain Formation.

Locally, individual conglomerate units may contain as much as 20 lbs. of more U_3O_8 per short ton, but over mining widths of the order of 2.7 to 9 m (9 to 30 feet) the average grade of those beds which are, or have been, mined is 2 to 3 lbs. of U_3O_8 per short ton. The fringe areas to mined beds, the lateral extension to the Quirke Zone, and the Pardee Zone contain considerable amounts of material with average grades of ½ lb. to 1½ lbs. U_3O_8 per short ton.

The arkose interbedded with the ore conglomerate is generally greenish in colour and is crossbedded (Roscoe 1966; J.A. Robertson 1968a, b, 1975a). Normally this crossbedding is of the festoon type indicative of a fluviatile environment.

The conglomerate was laid down in anastomosing or braided stream channels. Lateral migration resulted in the coalescing of these channels to form sheets.

AGNEW LAKE AREA

The deposits at Agnew Lake (Little *et al.* 1972) currently under development, comprise gritose oligomictic conglomerate interbedded with arkose in a quartzite sequence which is probably equivalent to the Matinenda Formation. The pebbles are smaller and more sparse than in the Blind River ore, and pyrite is less conspicuous than at Blind River-Elliot Lake. Thorium to uranium ratios are higher than at Blind River-Elliot Lake, reflecting the presence of uranothorite and monazite as the dominant radioactive minerals. Post-Huronian deformation is considerably greater, resulting in steep dips and in development of cleavage and stretched pebbles. Little *et al.* (1972) estimated the reserves at 8,000 short tons U_3O_8 in material grading 1.88 lbs. of U_3O_8 per short ton.

COBALT EMBAYMENT

That part of the Southern Province lying north of Sudbury is generally known as the Cobalt Plate (Card *et al.* 1972; Price and Douglas 1972); neither thrust faulting nor plate-tectonics have been recognized as significant factors in the regional geology. Douglas (1974a, b) prepared maps of the "Geological Provinces" and "Tectonics" of Canada for inclusion in the National Atlas of Canada (Fourth Edition) in which he used the designation Cobalt Embayment rather than Cobalt Plate as has been used in Figure IV-I in the Geology and Economic Minerals of Canada (GSC 1970), and Douglas's map (Douglas 1972) *in* Price and Douglas (1972) of the Principal Geological Elements of Canada. At present this improved nomenclature has not had wide usage amongst geologists. Lower Huronian rocks are intermittently exposed in the southern portion of the Cobalt Embayment, but

are largely concealed by Nipissing Diabase and upper Huronian rocks. The regional geology has been discussed by Thomson (1960) and by Meyn (1972). Precise stratigraphic correlation with Blind River is unclear, but rocks equivalent to the Mississagi Formation are present. At the base of these, wherever exposed, there are anomalous concentrations of uranium, and, at some localities, gold in conglomerates and uranium in argillaceous quartzites.

Early descriptions of the conglomerate (Thomson 1960; Meyn 1972; J.A. Robertson 1968a) compared these rocks with the Blind River-Elliot Lake oligomictic conglomerates. However, this comparison is invalid. Many of the conglomerates are polymictic, containing fragments of granite, "greenstone", and iron formation sparsely distributed in an argillaceous quartzite matrix. Many of the so-called quartz pebbles are actually quartzite of unknown provenance, or iron formation similar to that of nearby Archean "greenstone" belts. Showings in Vogt Township and Turner Township (Robertson 1968b) reportedly contain trace amounts of gold.

These deposits are clearly derived from Archean terrain, but are of different provenance than those at Blind River and Elliot Lake, and are perhaps slightly younger, but must be considered part of the same metallogenic province. Further prospecting and exploration in the southern part of the Cobalt Plate should yield more data of stratigraphic and hopefully of economic value.

PRODUCTION

Between 1955 and 1973, the Blind River-Elliot Lake camp has produced (from 12 mines) approximately 1.5 billion dollars worth or uranium, and minor amounts of thorium and yttrium from material grading 2 lbs. of U_3O_8 per short ton. The maximum production was in 1959, when 12,150 short tons U_3O_8 were produced. In 1973, two mines were operating: the Denison Mine produced 1,712 tons U_3O_8 from ore grading 2.57 lbs. of U_3O_8 per short ton, and the New Quirke Mine produced 2.409 tons U_3O_8 from ore grading 3.4 lbs. of U_3O_8 per short ton (1973 Annual Reports for Denison Mines Limited and Rio Algom Mines Limited). The Agnew Lake Mine north of Espanola has a developed ore body but the decision to start production would require a suitable sales contract (1975 Annual Report for Kerr Addison Mines Limited).

Ontario's current production is more than 4,000 short tons U_3O_8 per year, but the known deposits can support a production of between 11,000 and 14,000 short tons U_3O_8 per year, which can be obtained by expanding operating plants, reopening closed plants, and some construction of new plants.

RESERVES

It is estimated (J.A. Robertson 1975a) from data available to the public in January 1973, that Ontario deposits, predominately the sedimentary deposits of Blind River-Elliot Lake-Agnew Lake areas, contain, approximately 200,000 short tons of recoverable U_3O_8 with a millhead grade of

1.8 lbs. U_3O_8 per short ton and a further 150,000 short tons from material with a millhead grade of 1.4 lbs. of U_3O_8 per ton and a cut-off grade of 1 lb. of U_3O_8 per ton over mining widths. The higher grade uranium reserves also contain at least 100,000 short tons of recoverable ThO_2. The higher grade material constitutes some 75 percent of Canada's uranium reserves, and 17 percent of the free world's reserves recoverable at less than $10.00 U.S. (1973) per lb. of U_3O_8 (*cf.* Little 1974; Williams and Little 1973; OECD 1973). Estimated additional ore (possible ore and prognosticated ore) in the localities of the Blind River-Elliot Lake-Agnew Lake areas may be as much again, but extensive and costly exploration must be undertaken before existence of this material can be confirmed and considered part of the reserves.

ORIGIN OF THE URANIUM DEPOSITS OF BLIND RIVER-ELLIOT LAKE-AGNEW LAKE TYPE

The following discussion is largely taken from earlier summaries by the author (J.A. Robertson 1968a, 1969a).

Uranium and thorium mineralization occurs at a number of localities throughout the world in quartz-pebble conglomerates bearing appreciable pyrite, and, especially in the Witwatersrand in South Africa, gold in the matrix. The origin of these conglomerates has been much debated. The similarity of the deposits at Blind River-Elliot Lake-Agnew Lake to one or another of several of the well-known deposits at Witwatersrand (South Africa) and Jacobina (Brazil) have been pointed out by Bateman (1958), Davidson (1957, 1965), Derry (1960, 1961) Joubin (1960), and Gross (1968). Davidson also mentions similar deposits in Australia and Russia. This characteristic assemblage and its distribution is a major theme of the current symposium. The relationship to major unconformities (particularly those marking the Proterozoic-Archean boundary) has been emphasized (Derry 1961; Davidson 1965; J.A. Robertson 1960 *et seq.* and Thomson 1960). In the Blind River Camp this can be placed at 2,500 million years, and it is clear that the conditions did not persist beyond a minimum of 2,155 million years and that the period 2,500 to 2,400 million years seems the most favourable.

Bateman (1955, p.371), Joubin and James (1957), Davidson (1957, p.668) and Heinrich (1958) have cited the supposedly high uranium to thorium ratios, the high titanium to iron ratio and the association of Ti, Co, Ni, Th and U in a deposit carrying the characteristic minerals gold, brannerite, uraninite and pyrite as evidence of a hydrothermal origin. Patchett (1960), after a detailed study of only three samples from the Nordic Mine, regarded the ores as epigenetic. Joubin (1954, p.431-437) suggested the "Keweenawan" Diabase as a source, but in a later paper (Joubin 1960) admitted that mining evidence clearly indicated that diabase postdated the uranium mineralization. Davidson (1957) suggested that the (supposedly) post-Huronian granite lying to the southeast was the probable source. However, much of the granite formerly considered to be of possible post-Huronian age and shown as such on the Lake Huron Sheet (Geol. Surv. Canada, map 155A) has since been proved (J.A.

Robertson p.60, 1972; Ginn 1960, 61; Card *et al.* 1972) to be older than the Huronian. Only the Cutler Granite, exposed south of the Murray Fault 20 miles south of Elliot Lake, is now considered to be of post-Huronian age (J.A. Robertson 1964, 1972; Van Schmus 1964, 1965).

In 1965, Davidson (1965) returned to the question of the origin of banket orebodies, and considerably modified his earlier views. The revised hypothesis may be summarized as follows:

a) Deposition of molasse-type sediments in deep basins with conglomerate near the basal unconformity.
b) Leaching of the metal content (for Blind River-Elliot Lake-Agnew Lake uranium and thorium) by ground waters.
c) Prolonged series of intrastratal migration, allowing mineralized ground waters to sink to the lowest permeable horizons, the oligomictic conglomerate beds, where the metals would be reprecipitated.
d) The thermal energy for cycling groundwaters would be derived from post-sedimentation intrusions. For the Blind River-Elliot Lake-Agnew Lake area, the final cycle of ground water took place during the Hudsonian (Penokean) orogeny, as evidenced by the 1,700 million years age for uraninite and brannerite obtained by Mair *et al.* (1960). However Roscoe (1969) showed that the isotopic compositions are best explained by the resetting rates rather than by introduction of new material.

Abraham (1953) and McDowell (1957, 1963) regarded the ores as fossil placer deposits. Pienaar (1958, 1963) and Roscoe (1957 *et seq.*) have also indicated a preference for a placer origin. D.S. Robertson (1962a, 1962b) has also assembled much data, particularly on U/Th ratios, that is suggestive of a placer origin. Holmes (1957) suggested that the ores were of syngenetic (placer) origin but were modified by later events.

Derry (1960) has also suggested a syngenetic origin for the uranium mineralization, but has raised the possibility that the uranium was largely carried in solution and reprecipitated in gravel banks by bacterial agencies. Joubin (1960) has published similar ideas, but has not included bacterial precipitation.

It may be noted that other conglomerates in the district (i.e., the Matinenda polymictic conglomerate, and the Ramsay Lake, Bruce and Cobalt conglomerates) do not carry markedly high uranium values, although all, and particularly the Bruce, carry pyrite and pyrrhotite. An exception to this occurs when such a conglomerate unconformably overlies the uranium-bearing sequence or infringes on the basement (J.A. Robertson 1968a, 1969a). It should be noted that the red granitic bodies in the basement are radioactive (J.A. Robertson 1960, 1967).

The sericitic matrix of the ore-bearing conglomerates is similar to the sericitic paleosoil, and was probably derived from it; there is no necessity to suppose that it was produced by the passage of hydrothermal solutions. Uraniferous oligomictic pebble conglomerates and a green arkose sequence are characteristic of whichever part of the Huronian sequence overlies the basement in the area of the North Shore of Lake Huron, and these rocks

show a progressive northward overlap. Significant thicknesses and grades have so far been found only in the Matinenda Formation.

Quartz veins and other evidence of intense hydrothermal activity are not conspicuous in the rocks of the area, and bear no sympathetic relationship to the uranium deposits. Where found, the associated mineralization is of copper and other sulphide minerals. Within the Blind River-Elliot Lake-Agnew Lake camp, there is no indication that either the Nipissing Diabase (formerly included with the Keweenawan) or the olivine diabase intrusions are a possible source of major radioactive mineralization. There is, however, evidence that ores were subjected to local intense alteration and that all rocks suffered sulphide mineralization at the time of the intrusion of the Nipissing Diabase and the regional folding. Age-determination data is consistent with this concept.

The over-all distribution of beds and the behaviour of thickness and grades are more consistently explained by the modified placer hypothesis, which the author has supported (J.A. Robertson 1960 *et seq.*).

The recent mineragraphic studies of Ferris and Ruud (1971) and Theis (1973) have added to the basis of the modified placer hypothesis.

The deposits were derived from Archean terrain to the north and northwest, transported by rapidly moving water, deposited in a near shore fluviatile environment under cold, possibly frigid reducing conditions about 2,500 million years ago, and later subjected to diagenesis and to minor alteration during subsequent intrusive metamorphic and tectonic events.

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